

# Performance of a bipolar single electron device

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A small scale bipolar transistor with polysilicon emitter will, depending on the emitter window size, display suppression of the hole transport due to single electron effects. In this paper the resulting base current suppression is computed in terms of the orthodox theory of single electron tunneling and a recombination time approximation. The possible application of the transistor as readout system for Coulomb blockade device circuits is discussed.

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**Introduction** – The appeal of bipolar transistors is their appreciable current drive  $\beta = I_c/I_b > 100$ . The use of polysilicon (poly-Si) emitters has helped to maintain this figure of merit despite increasing challenges from continuous down-scaling<sup>1</sup>. The effect of the new material is attributed to the poly-Si grain boundaries obstructing the hole transport thus reducing  $I_b$  and increasing  $\beta^{2,3}$ . Point contact measurements of a few poly-Si grains resulted in effective grain boundary energy barriers of up to 80 meV which translates into three times room temperature. These findings correspond roughly to the values found in molecular dynamics simulations<sup>4</sup>.

This work studies the performance of radically scaled bipolar transistors with small emitter windows, especially the hole transport in the poly-Si emitter. For these devices single electron effects can be expected, *i.e.* charged grains prevent subsequent holes from entering. Thus the hole current is further reduced and the current drive  $\beta$  enhanced.

The studied device is similar to the tunnel emitter transistor<sup>5,6</sup> insofar as it uses tunnel barriers in the emitter to reduce the base current. Otherwise the two devices are very dissimilar: the tunnel emitter transistor employs a metal emitter that can electrically induce the transistor's base region.

The studied bipolar transistor differs fundamentally from the single hole transistor<sup>7</sup>. The former is a rather classical device involving a mesoscopic effect for the enhancement of its operation while the latter is a true mesoscopic device similar to the single electron transistor<sup>8</sup>.

Single electron effects in poly-Si have been reported since 1994<sup>9,10</sup>. Single grains of a very thin (less than 10 nm) undoped poly-Si films could be charged by applying a large gate bias (44...60 V). This charging resulted in a noticeable hysteresis of the  $I_d-V_{gs}$  characteristics. A grain capacitance of  $\sim 2$  aF was deduced from the hysteresis.

Heavily doped poly-Si nanowires ( $5 \times 10^{19} \text{ cm}^{-3}$ ) of larger cross section ( $20 \times 30 \text{ nm}^2$ ) showed single electron effects at low temperature (4.2 K)<sup>11,12</sup>. Again, the grain capacitance as deduced from electrical measurements was  $\sim 2$  aF while the average grain size is estimated to  $\sim 20$  nm.

**Method** – The simulation of the poly-Si emitter must feature charging effects for the device under considera-

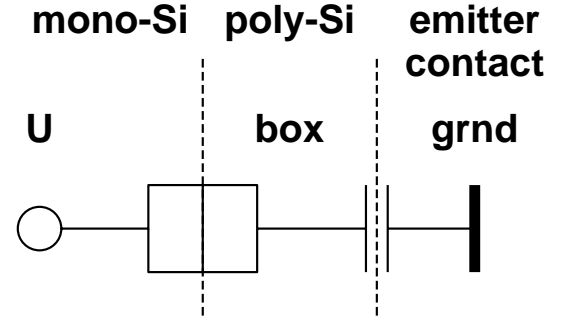


FIG. 1: Schematic illustration of the single electron box model used in this paper. The transistor base is to the left, the emitter contact to the right. An injection voltage  $U$  forces holes into the poly-Si emitter, *i.e.* the single electron box, where the holes fall victim to recombination.

tion. To this end the model of a single electron box<sup>13,14</sup>, see Fig. 1, is used. The box represents a single grain of the emitter. It lives between a tunnel junction (base side) and a capacitance (emitter contact side). This model is a stark simplification of the real poly-Si emitter insofar as it excludes hole transport into the emitter contact and assumes only one grain wide emitters. The first assumption is often close to the truth since the emitter width is designed to exceed the hole diffusion length. As for the second simplification, a single electron trap model<sup>15</sup> might be more appropriate, but its simulation is numerically more involved and its behavior does not qualitatively deviate from that of a single electron box in the current context.

The state of a single electron system in an orthodox situation is given in terms of the charge number states of each of its island electrodes, which form good quantum numbers<sup>16</sup>. The single electron box consists of one island and the number of excess charges  $n$  on this island suffices for the description.

In the original model of the single electron box<sup>13,14</sup> there is no average net current in or out. In the case of the poly-Si emitter the hole current arises due to recombination. Therefore a recombination model is added to the box description. A constant recombination time  $\tau_{\text{rec}}$

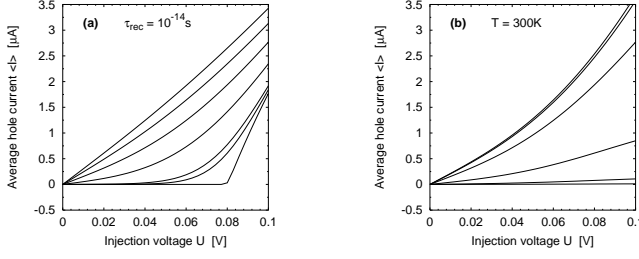


FIG. 2: Hole current into the poly-Si emitter as function of the injection voltage  $U$ . The box parameters are  $C_g = C = 1$  aF,  $R = 10$  k $\Omega$ . (a) Temperature dependence, the data correspond to 4.2 K, 77 K, 100 K, 200 K, 300 K, 400 K, and 500 K (from bottom to top),  $\tau_{\text{rec}} = 10^{-14}$  s. (b)  $\tau_{\text{rec}}$  dependence, the data correspond to  $10^{-11}$  s,  $10^{-12}$  s,  $10^{-13}$  s,  $10^{-14}$  s,  $10^{-15}$  s,  $10^{-16}$  s (from bottom to top),  $T = 300$  K.

is assumed leading to a recombination rate of a state  $n$

$$\Gamma_{\text{rec}}[n \rightarrow n - \text{sgn}(n)] = \frac{|n|}{\tau_{\text{rec}}}, \quad (1)$$

$\Gamma[n \rightarrow m] = 0$  for  $m \neq n - \text{sgn}(n)$ .

The recombination rate  $\Gamma_{\text{rec}}[n \rightarrow n \pm 1]$  is added to the corresponding single electron tunneling rate  $\Gamma_{\text{set}}[n \rightarrow n \pm 1]$  which is extensively discussed in the literature<sup>17</sup>

$$\Gamma_{\text{tot}}[n \rightarrow n \pm 1] = \Gamma_{\text{rec}}[n \rightarrow n \pm 1] + \Gamma_{\text{set}}[n \rightarrow n \pm 1].$$

The total rates  $\Gamma_{\text{tot}}[n \rightarrow n \pm 1]$  are used to set up an orthodox master equation for the evolution of probability of the state  $n$ ,  $dp(n, t)/dt$ <sup>18</sup>. This equation possesses a well-known stationary solution<sup>19,20</sup>,  $p(n)$ , which holds for processes slow compared to  $1/\Gamma_{\text{tot}}$ . It is used in the current context to express the stationary average injection current  $\langle I \rangle$ , which is plotted in Fig. 2.

*Discussion* – Which are the geometric requirements for the observation of the discussed effect? The emitter structure corresponds to a vertical setup of the poly-Si films discussed before. In the foreseeable future it will be impossible to use films of the dimension of Refs. 9,10. However, condition are more relaxed for the application under discussion because retention time is no issue. Structures of the type of Refs. 11,12 suffice in the current context and an emitter window of  $50 \times 50$  nm<sup>2</sup> appears likely to be required.

The apparatus of the orthodox theory applies only to systems satisfying  $R > \hbar/e^2 \approx 6.45$  k $\Omega$ . Otherwise,  $n$  is no good quantum number anymore and quantum fluctuations lead to a larger hole current<sup>21</sup>. The grain boundary resistance of a poly-Si film, like other material parameters, depends strongly on the process conditions. However following Ref. 22, it can be purported that the orthodox theory is applicable in certain instances.

The injection voltage  $U$  can be expressed by means of Boltzmann statistics in the low injection approximation,  $U = k_B T/e \approx 26$  mV for room temperature. In contrast, the number of injected charges is given by the base voltage  $V_{be}$ .

The hole currents of Fig. 2 can be set in relation to the recombination current without Coulomb blockade,  $e/(RC + \tau_{\text{rec}}) \approx 10^{-5}$  A. Therefore an injection reduction to 0.1 can be expected for the given parameters. Conventionally  $\tau_{\text{rec}}$  is assumed to exceed the assumed value  $10^{-14}$  s considerably thus furthering the performance enhancement of the Coulomb blockade emitter.

Besides injection into the emitter (and subsequent recombination), holes recombine in the quasi-neutral base and the emitter-base space charge region. The influence of the different recombination processes on the current drive  $\beta$  is conveniently by the partial values  $\beta_1$  (quasi-neutral base),  $\beta_2$  (space charge region), and  $\beta_3$  (emitter injection),

$$\beta = \frac{1}{1/\beta_1 + 1/\beta_2 + 1/\beta_3}.$$

Typical values are  $\beta_1 \approx 10^6$  and  $\beta_2 \approx 10^3$  for modern devices so that  $\beta_{1,2} \gg \beta_3$  and  $\beta \approx \beta_3$ . The performance gain of Coulomb blockade emitter devices is limited by  $\beta = 1/(1/\beta_1 + 1/\beta_2) \approx 10^3$ .

Purportedly, there is an indirect influence of the emitter operation on the electron current. The Coulomb blockade of holes leads to an reduced hole diffusion length as well. Thus, the emitter design can use thinner poly-Si layers which reduces the emitter delay of the electrons in turn.

The down-scaled bipolar transistor might serve as a current multiplier or readout device for Coulomb blockade circuits. It is well known that besides many advantageous features single electron transistors display a low current gain  $\beta \approx 1$ , which, among others, limits their use for logic applications. It can be envisioned that the transistor studied in this paper can be used as a current multiplier. Given a single electron transistor output current of  $\sim 1$  nA, a current amplification of  $\beta = 10^3$  would lead to much more manageable currents. For instance, MOSFET sensing operating with voltage swings of  $\Delta V \approx 100$  mV, would require a load resistance of 1 k $\Omega$ , which is thoroughly feasible.

*Conclusions* – The performance of a small emitter window size bipolar transistor is studied assuming Coulomb blockade effects in the poly-Si emitter. A reduced hole injection current is found leading to an improved current drive  $\beta$ . The transistor is discussed as readout device for Coulomb blockade systems.

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